Mixed Layer Response to Monsoonal Surface Forcing in the Arabian Sea

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LONG-TERM GOALS

Our long-range objective is to observe and understand temporal and spatial variability of the upper ocean and identify the role of air-sea interaction in determining that variability. We seek to do this over a wide range of environmental conditions in order to improve understanding of upper ocean dynamics and of the physical processes that determine the vertical and horizontal structure of the upper ocean.

OBJECTIVES

Prior to the Arabian Sea Mixed Layer Dynamics Experiment, most efforts to understand air-sea interaction and upper ocean variability had been carried out in areas characterized by moderate to light atmospheric forcing or by episodic strong forcing. Little work had been done in a region characterized by strong, sustained forcing; and the separation of oceanic variability due to atmospheric forcing from that associated with mesoscale variability has been difficult. Thus, the combination of strong, sustained monsoonal forcing with summer and winter mixed layer deepening, calm intermonsoons with strong heating, and energetic mesoscale variability associated with eddies and coastal jets characteristic of the Arabian Sea presented a unique opportunity.

Our objective was to test the following hypotheses: (1) Upper ocean response in the Arabian Sea is well-described by one-dimensional physics and biology. (2) Large scale, wind stress curl driven vertical velocities at the base of the mixed layer significantly affect the temporal evolution of the mixed layer; (3) Summer cooling of the mixed layer results from either increased cloud cover, large latent heat loss, lateral advection of cool water upwelled along the Somali and Arabian coasts, upwelling associated with Ekman suction, entrainment at the base of the mixed layer or from a combination of these processes; (4) After the onset of the monsoons, further entrainment at the base of the mixed layer is dominated not by near-inertial shears but by shears associated with sub-inertial wind-driven flow; and (5) Three-dimensional flow associated with mesoscale ocean variability rather than large-scale, wind-stress curl driven flow is the primary source of vertical circulation at the base of the mixed layer.

APPROACH

The ONR-sponsored Arabian Sea Mixed Layer Dynamics experiment was designed to observe and better understand the physical and bio-optical variability of the upper ocean in the Arabian Sea. As a part of this experiment, we deployed an array of surface and subsurface moorings in cooperation with Rudnick (SIO), Eriksen (UW), Dickey (USC), and Marra (LDEO), from October 1994 through October 1995. The array was located just south of the climatological maximum of the Findlater jet in the north-central Arabian Sea at 15.5°N, 61.5°E (see Fig. 1), in a square about 50 km on a side. The

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two western elements (SIO) were surface toroid buoys carrying some meteorological instrumentation, a downwards-looking ADCP, and supporting a chain of temperature sensors. The two eastern elements (UW) were subsurface profiling current meters. The central WHOI mooring was a completely instrumented discus buoy supporting temperature, velocity, and salinity sensors.

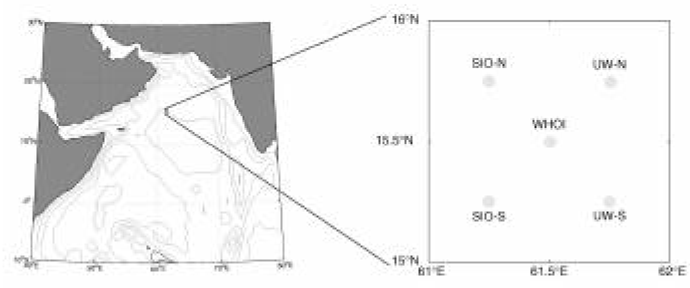

Figure 1. The location of the five-element moored array in the north central Arabian Sea. The array was approximately 50 km on each side.

The WHOI surface buoy was equipped to collect high quality meteorological data. These observations led to complete and accurate measurements of the air-sea exchanges of heat, freshwater, and momentum, and support a description of the evolution of the vertical structure of the velocity, temperature, and salinity fields in the upper ocean at that point. Current meters, temperature recorders, and temperature/conductivity recorders were deployed on the WHOI surface mooring to resolve the vertical structure of the upper ocean. Additional WHOI current meters and temperature recorders were deployed on one of Eriksen's PCM moorings to extend our observations over the entire depth of the Arabian Sea at this location. Bio-optical and acoustic instrumentation (Langdon, URI; Dickey, USC; Marra, LDEO; Holliday, Tracor) were also deployed on the WHOI surface mooring, which was recovered and redeployed in April 1995. The UW and SIO moorings were deployed to provide the ability to determine horizontal advection and examine horizontal variability. Additional data sets (ECMWF, NMC, satellite, climatological, and concurrent ship reports) have been obtained to describe the forcing fields and the broadscale response. The WHOI mooring and instrumentation was documented in three cruise reports (Trask *et al.*, 1995a and b; Ostrom *et al.*, 1996), and a data report (Baumgartner *et al.*, 1997) was published last year.

WORK COMPLETED

The field program provided an unprecedented look at the response of the mixed layer to the wide range of surface forcing found to be associated with the annual cycle in the Arabian Sea. Scientific analyses and publication are in progress. The effort has focused on completing the analysis of the surface meteorological and air-sea flux fields at the moored array and over the Arabian Sea, on developing a description of the observed upper ocean variability, and a preliminary assessment of the ocean dynamics at the moored array.

The work on the surface forcing developed into a collaboration with Peter Taylor and Simon Josey of the Southampton Oceanography Centre (SOC) in the U. K., in which the data from our surface mooring was used to verify the significant improvements they have made in correcting volunteer observing ship

data and in making regional choices for appropriate bulk flux formulae. This work was included in the paper summarizing the analysis of the surface forcing submitted to *the Deep-Sea Research* Arabian Sea volume (Weller *et al.*, 1998).

We have used gridded wind fields from numerical weather prediction models to estimate the magnitude of the Ekman pumping. In collaboration with Dickey and Robert Leben (CCAR, U. Colorado) we have been using combined TOPEX/ERS altimetry and derived surface velocities to help interpret the mooring record.

The oceanic variability at our mooring has been examined; two periods of mixed layer deepening and cooling associated with the NE and SW Monsoons are well documented. Analyses of both the bio-optical and physical variability observed at our mooring have been reported in Dickey *et al.* (1998), Marra *et al.* (1998), and Wiggert *et al.* (1998). The upper ocean heat budget has been examined using an estimate of the horizontal heat flux derived from the moored array. The significant contribution of mesoscale features to the heat budget is well resolved.

RESULTS

Our observations confirm that there are errors in some widely used flux climatologies. They also show a striking difference in surface forcing between the monsoons. The NE Monsoon has moderate winds and strong oceanic surface heat and freshwater loss, while the SW Monsoon has strong winds, significant oceanic heat gain, and reduced evaporation (see Fig. 2).

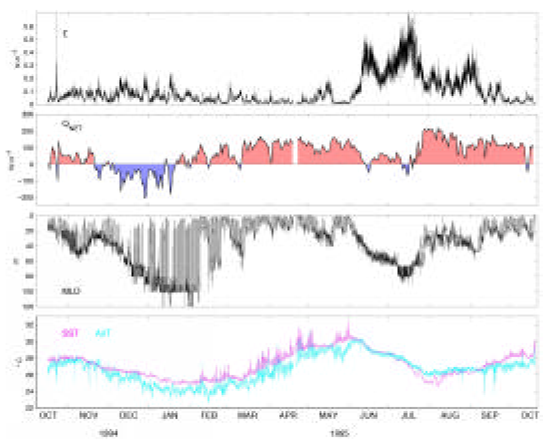

Figure 2. The wind stress, net heat flux, mixed layer depth, and air and sea surface temperatures for the one-year deployment. The NE monsoon (Nov.-Jan.) is characterized by moderate wind stress and an oceanic heat loss, leading to a deepening of the mixed layer with strong diurnal cycling and a cooling of the sea surface temperature. The SW monsoon (June-Aug.) is characterized by very strong wind stresses and moderate oceanic heat gains, and a second cycle of mixed layer deepening and cooling.

A striking result of the examination of the wind fields from ECMWF analysis is that the Findlater Jet is not, except in monthly mean fields, a well-defined structure, a result supported by Kindle's model-based surface wind fields. As a result, there are not well defined, persistent regions of negative and positive

wind stress curl associated with the Jet. At the site of the moored array, in particular, Ekman pumping is estimated to play an insignificant role in mixed layer dynamics. During the monsoons, wind direction is remarkably stable; however, wind magnitude is highly variable in space and time. This suggests that transient Ekman pumping may occur and that even during the monsoons; the wind may be able to excite near-inertial motions in the ocean.

The deepening in the winter of 1994-1995 was driven largely by the strong surface buoyancy flux and the resultant convection in the upper ocean. In contrast, and because there is in fact no sustained surface heat loss, that observed in the summer of 1995 was associated primarily with wind-driven mixing. In both cases, though, other effects are apparent. The passage of an eddy influences the mixed layer depth and dominates the surface velocity variability during the onset of the NE Monsoon, and offshore advection of cool water contributes to the local heat budget during the onset of the SW Monsoon. Further evidence that the eddies play a role in mixing processes in the upper ocean has come from the bio-optical and bio-geochemical observations. There were four blooms of phytoplankton; two were associated with the restratification of the mixed layer and two with the passage of eddies (Marra *et al.*, 1998; Dickey *et al.*, 1998). A sediment trap mooring located near the moored array shows peaks in the downward particle flux in the interior correlated with the four blooms (Honjo and Weller, 1997; Honjo *et al.*, 1998). Variability in the chemical composition of the particles suggests that the passage of the eddies was accompanied by vertical mixing that brought nutrients to the surface from the interior.

The horizontal resolution of the moored array allows an estimation of the horizontal gradients in temperature, and when combined with velocity information, the horizontal flux of heat through the array. The data coverage of the array provided at least three independent estimates of temperature and velocity with depth during the entire one-year deployment. The vertically integrated heat budget can be written as the sum of three terms, the temperature trend (which can be directly calculated from the data), the horizontally advective heat flux (which can be estimated from the array), and the surface heat flux (measured), with a residual due to the vertical advection of heat.

The vertically resolved horizontal heat flux shows the strong influence of mesoscale eddies, and significant differences between the two monsoons (see Fig. 3). During the NE monsoon (Nov.-Jan.) there is a significant heating at the base of the mixed layer, while there is little advection of heat within the mixed layer despite strong velocities, indicating that the horizontal variability is largely confined to a varying topography of the base of the mixed layer. This is consistent with satellite data and a pre-deployment XBT survey which both show remarkable spatial uniformity in sea surface temperature during the NE Monsoon. At the site of the mooring, this subsurface warming also contributed to the depth of the mixed layer, as reduced stratification allowed convection to entrain deeper water. During the SW Monsoon there is significant cooling throughout the water column in June, and the sharp signature of an eddy passing in late July and early August. The vertically integrated heat flux shows that at times when a one-dimensional heat balance fails, the primary balance appears to be between the temperature trend term and the horizontal advection of heat. During those two periods these terms are far larger than the surface heat flux.

To date, then, we have made good progress toward testing the five hypotheses listed at the end of the Background section. We have improved our understanding of the surface forcing, investigated the processes responsible for the response of the upper ocean, and tested the extent to which 1-dimensional physics describes the observed variability.

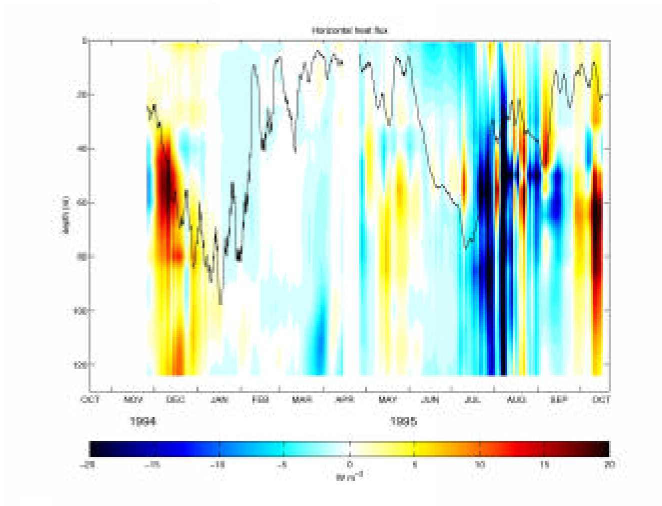

Figure 3. The vertically resolved horizontal heat flux. The thick black line is the base of the mixed layer. A strong warming heat flux took place at the base of the mixed layer during the NE monsoon, while during the SW monsoon fluxes occurred throughout the water column, though concentrated in the upper thermocline.

IMPACT/APPLICATIONS

The field work produced the first long time series of high quality near-surface meteorology and air-sea fluxes of momentum, heat, and freshwater to be obtained in the Arabian Sea. This will permit critical evaluation of existing climatologies and atmospheric models. Already, comparisons indicate shortcomings in both as sources of information about heat and freshwater fluxes and support use of the new SOC climatology for further studies of the Arabian Sea. The buoy and SOC data indicate strong heat gain in the summer over the central Arabian Sea, strengthening the case for the dominance of wind-mixing and advection as the mixed layer cools and indicating the need to re-examine basin scale heat budgets and inferences of meridional circulation based upon them.

TRANSITIONS

In both projects surface meteorological data was telemetered via satellite and after recovery made available to forecast centers. IMET (Improved METeorological) sensors as used on Arabian Sea buoy under have been installed in a trial on an Aegis cruiser, and a dialog started about the need for better forecasts for the Navy of the atmosphere and ocean in the Arabian Sea

RELATED PROJECTS

This work has resulted in ongoing cooperative projects with numerical modeling, satellite remote sensing, JGOFS, and WOCE studies in the Arabian Sea.

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